ORIGIN OF OUTER SOLAR SYSTEM

GRANT NAG5-9678

FINAL REPORT

For the period 01 June 2000 through 31 August 2002

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January 2003

Prepared for

National Aeronautics and Space Administration

Washington, D.C.

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The Smithsonian Astrophysical Observatory
is a member of
Harvard-Smithsonian Center for Astrophysics

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I Progress in the Final Year

We feel that at the present moment the available theoretical models of the Kuiper belt are still in advance of the data, and thus our main task has been to conduct observational work guided by theoretical motivations. The table below lists our telescope time allocations from 2001 to the present. These amount to 86 nights in 2001 and 56 nights to date in 2002. Our efforts over the past year can be divided into four categories:

A. Wide-field Searches for Kuiper Belt Objects

As of April 2002, we have conducted several searches for Kuiper belt objects using large-format mosaic CCD camera on 4-meter class telescopes. In May 1999, we used the Kitt Peak 4-meter with the NOAO Mosaic camera we attempted a search for KBOs at a range of ecliptic latitudes. This run was lost to poor weather. We will repeat this search in May 2000. In July 1999, we conducted a search near Uranus and Neptune with the CFH12K mosaic on the Canada-France-Hawaii 3.6-meter telescope. Although this survey was designed detected Uranian and Neptunian moons, we detected approximately fifty KBOs in the background. We were able to follow up and report 16 of these objects. In March 2000, we conducted another wide-field search for KBOs with the CFH12K on the CFHT. Again, poor weather limited our results. However, we were able to detect and report discoveries of eight new KBOs. In Aug 2000, I re-searched the regions near Uranus and Neptune where we had searched for satellites in the previous year. The search fields were selected to encompass the region where the KBOs discovered in the previous search would now be. This not only allowed many of those KBOs to be recovered but 19 many new KBOs were discovered and reported. Addition searches for Kuiper belt objects were conducted at CFHT in July, August, and November 2001, as well as March 2002.

The combination of ecliptic longitudinal coverage and range of ecliptic latitudes that we have searched and plan to search will allow us to constrain the relative populations of different classes of KBOs as well as to constrain their inclination distributions.

B. Pencil-beam Searches for Kuiper Belt Objects

In addition to our wide-field searches, we have conducted three "pencil-beam" searches in the past year. In a pencil-beam search we take repeated integrations of the same field throughout a night. After preprocessing the resulting images we shift and recombine them along a range of rates and directions consistent with the motion of KBOs. Stationary objects then smear out, while objects moving at near the shift rate appear as point sources. We have not only demonstrated and refined this technique, but it allows us to reach two full magnitudes below the single exposure detection limit in a night of integration. The final scientific result from a pencil-beam search is measure of the sky surface density at a particular ecliptic longitude and

latitude. As with the wide-field searches, our pencil-beam surveys have been conducted at a range of ecliptic longitudes and latitudes. This, again, allows to map out the sky distribution of KBOs, guiding future searches. So far in 1999-2000 we have discovered and followed 16 faint KBOs in our pencil-beam searches.

C. Wide-field searches for Moons of the Outer Planets

In addition to our searches for Kuiper belt objects, we are completing the inventory of the outer solar system by search for faint satellites of the outer planets. As mentioned above, in July 1999 we conducted a search for Uranian and Neptunian moons at the CFHT. Our efforts were rewarded with the discovery of three new irregular satellites of Uranus.

Through the fall and winter of 2000 we conducted a wide-field search for Saturnian moons using a variety of observing platforms. This resulted in the discovery of 12 new Saturnian irregular satellites. One of the most intriguing results of those discoveries is the clustering in orbital elements that can be seen. Just as the Jovian irregular satellites showed inclination families, now Uranus and Saturn show similar families. Own analysis suggests that the smaller members of each family are collisional fragments of the biggest member.

D. Pencil-beam Searches for faint Uranian and Neptunian Moons

Our 1999 search of the region around Neptune resulted in the detection of no new moons. Initially we believed that this simply supported the theory of Goldreich *et al.* 1989 that the capture of Triton disrupted the Neptunian satellite system. However, the recent discovery of small Saturnian (and Jovian moons) suggests the existence of small Neptunian moons below our previous detection threshold. In August 2001 we conducted pencil beam searches for faint Uranian and Neptunian satellites at CFHT and CTIO. These searches resulted in the discover of two Neptunian and four Uranian satellite candidates. Poor weather during follow up opportunities prohibited us from determining the orbits of these objects with sufficient accuracy to firmly establish them as moons. We have asked for time at CTIO in August 2002 to repeat this search. We have already searched follow up time at Magellan, the VLT, and Palomar.

E. Recovery Observations

The discovery of Kuiper belt objects and outer planet satellites is of little use if the discoveries are not followed by systematic, repeated astrometric observations that permit reliable estimates of their orbits. This inglorious task is necessary to achieve the scientific goals of our program. And, as the table below indicates, more than half of our observing time has been dedicated to follow up observations.

One of the object that we consistently tracked over the past year has a peculiar orbit. Its large semimajor axis (216 AU) and eccentricity (e=0.8) indicate that it is a scattered disk object, however it large perihelion distance (q=44 AU) is larger than any other known scattered disk

object. Our analysis suggested that the scattered disk has an extended component comprised of such large perihelion objects. Without our recovery and follow up efforts, this object would likely have been lost since its final orbit is significantly different from that initially assumed.

Dates	Nights	Telescope	PI	Project
2001 Jan 18-22	5.0	Pal 5-m	Nicholson	Tracking of satellites/TNOs
2001 Jan 17-18	2.0	MMT 6.5-m	Holman	TNO recovery work
2001 Jan 19-22	4.0	MH 1.2-m	Holman	TNO recovery work
2001 Jan 29-30	2.0	ESO 3.6-m	Petit	Recovery.
2001 Feb 22-23	2.0	VLT UT1 8-m	Gladman	Recovery of distant TNOs
2001 Feb 14-18	4.0	NOT 2.6-m	Holman	Recovery
2001 Mar 22-Apr 1	11.0	MDM 1.3-m	Chaboyer/Holman	Wide-field search
2001 Apr 21-22	2.0	MMT 6.5-m	Holman	TNO recovery work
2001 May 23-24	2.0	VLT UT2 8-m	Gladman	Search for cold disk
2001 May 26-31	7.0	VATT 1.8-m	Hergenrother/Holman	TNO recovery work
2001 Jun 17-18	2.0	MMT 6.5-m	Holman	TNO recovery work
2001 Jun 23-25	3.0	CFHT 3.6-m	Gladman/Doressoundiram/Veillet	Photometry/recovery
2001 Jul 21-22	1.3	CFHT 3.6-m	Kavelaars	Pencil beam search
2001 Jul 23-26	4.0	CFHT 3.6-m	Gladman/Doressoundiram/Veillet	Wide-field search
2001 Aug 11-13	3.0	CFHT 4m	Gladman/Doressoundiram/Veillet	Recovery/photometry
2001 Aug 9-12	4.0	CTIO 4m	Holman	Satellite pencil-beam search
2001 Aug 23-24	3.0	CFHT 4m	Kavelaars	Neptune satellite search
2001 Aug 19-22	4.0	Cal 2m	Petit	Recovery
2001 Sep 14-17	2.0	Mag 6.5m	Holman	Recovery
2001 Sep 17-20	4.0	Pal 5m	Nicholson	Recovery
2001 Oct 15-22	8.0	MH 1.2m	Holman	Jovian satellite search
2001 Nov 7-10	4.0	CFHT 4m	Gladman/Doressoundiram/Veillet	Discovery
2001 Nov 13-15	2.0	VLT 8m	Gladman/Petit	Recovery
2001 Dec 10-15	6.0	NOT 2.5	Grav	Recovery/Satellite photometry
2001 Dec 12,14	2.0	MMT 6.5m	Holman	Recovery
2002 Jan 12-13	2.0	NOT 2.5	Grav	Satellite photometry
2002 Feb 8-11	2.0	Mag 6.5m	Holman	Recovery
2002 Mar 6-13	8.0	Cal 2m	Campo	Recovery
2002 Mar 12-13	2.0	MMT 6.5m	Holman	Recovery
2002 Mar 14-15	2.0	NOT 2.5	Grav	Recovery/Satellite Photometry
2002 Mar 19-21	3.0	CFHT 4m	Gladman/Doressoundiram/Veillet	Discovery
2002 Apr 5-6	2.0	MMT 6.5m	Holman	Recovery
2002 Apr 12-15	2.0	Mag 6.5m	Holman	Recovery
2002 May 11-12	2.0	NOT 2.5	Grav	Recovery
2002 June 2,3,6,7	4.0	Pal 5m	Burns/Carruba	Search/Recovery
2002 Jun 4-6	3.0	CFHT 4m	Gladman/Doressoundiram/Veillet	Recovery/photometry
2002 June 6-8	3.0	Cal 3.5m	Petit/Campo	Recovery
2002 Jun 14-19	5.0	KPNO 2m	Parker et al	Recovery
2002 Jul 4-7	4.0	KPNO 4m	Parker et al	Recovery
2002 Jul 11-18	7.0	KPNO 2m	Parker et al	Recovery
2002 Sep 2-3	2.0	NOT 2.5	Grav	Recovery
2002 Sep 2-4	3.0	VLT UT1	Gladman/Petit	Recovery

Table 1: 2001-2002 Telescope allocations. A total of 86 nights were allocated to and observed by our team in 2001. So far in 2002 we have been allocated 56 nights, with 23 nights observed to date. Note: CFHT = Canada-France-Hawaii Telescope, NOT = Nordic Optical Telescope, MH = Mount Hopkins, KPNO = Kitt Peak National Observatory, VLT = Very Large Telescope, ESO = European Southern Observatory, Cal = Calar Alto, Mag = Magellan

II Publications resulting from work supported by this grant

Gladman B, Kavelaars J, Petit J-M, Morbidelli A, Holman M, Loredo T (2001) The Structure of the Kuiper Belt: Size Distribution and Radial Extent. *Astron. J.*, **122**, 1051-1066.

The size distribution in the Kuiper Belt records physical processes operating during the formation and subsequent evolution of the solar system. This paper reports a study of the apparent magnitude distribution of faint objects in the Kuiper Belt, obtained via deep imaging on the Canada-France-Hawaii Telescope and the ESO Very Large Telescope UT1. We find that the entire range of observed objects (magnitudes $m_R \sim 20 - 27$) is well represented by an unbroken power law, with the number of objects per square degree brighter than magnitude R being of the form $\Sigma(m_R < R) = 10^{alpha(R-R0)}$, with $\alpha = 0.69$ and $R_0 = 23.5$. This luminosity functions slope implies a steep size distribution in the observed range, which should "roll over" to a shallower "collisional" slope once observations extend to even fainter magnitudes and thus sample bodies whose collisional ages become less than the age of the solar system. Our observations indicate the roll over is for diameters of less than 50 km, in agreement with collisional models. Modeling our survey gives a belt mass between 30 and 50 AU of order $0.1 M_{\oplus}$, relatively insensitive to the roll over diameter as long as the latter is ~ 1 km. We report the discovery of several objects outside of 48 AU and discuss the evidence for a sharp outer edge to the trans-Neptunian distribution.

Gladman B, Kavelaars J, Holman M, Nicholson P, Burns J, Hergenrother C, Petit J-M, Marsden B, Jacobson R, Gray W, Grav T (2001) Discovery of 12 satellites of Saturn exhibiting orbital clustering. *Nature*, **412**, 163-166.

The giant planets in the Solar System each have two groups of satellites. The regular satellites move along nearly circular orbits in the planets orbital plane, revolving about it in the same sense as the planet spins. In contrast, the so-called irregular satellites are generally smaller in size and are characterized by large orbits with significant eccentricity, inclination or both. The differences in their characteristics suggest that the regular and irregular satellites formed by different mechanisms: the regular satellites are believed to have formed in an accretion disk around the planet, like a miniature Solar System, whereas the irregulars are generally thought to be captured planetesimals. Here we report the discovery of 12 irregular satellites of Saturn, along with the determinations of their orbits. These orbits, along with the orbits of irregular satellites of Jupiter and Uranus, fall into groups on the basis of their orbital inclinations. We interpret this result as indicating that most of the irregular moons are collisional remnants of larger satellites that were fragmented after capture, rather than being captured independently.

Gladman B, Holman M, Grav T, Kavelaars J, Nicholson P, Aksnes K, Petit J-M (2001) Evidence for an extended scattered disk. *Icarus*, **157**, 269-279.

By telescopic tracking, we have established that the trans-neptunian object (TNO) 2000 CR_{105} has a semimajor axis of 220±1 AU and perihelion distance of 44.14±0.02 AU, beyond the domain which has heretofore been associated with the 'scattered disk' of Kuiper Belt objects interacting via gravitational encounters with Neptune. We have also firmly established that the TNO 1999 TL_8 has a high perihelion (of 40.08±0.02 AU). These objects, and two

other recent discoveries which appear to have perihelia outside 40 AU, have probably been placed on these orbits by a gravitational interaction which is *not* strong gravitational scattering off of any of the giant planets on their current orbits. Their existence may thus have profound cosmogonic implications for our understanding of the formation of the outer Solar System. We discuss some viable scenarios which could have produced these objects, including long-term diffusive chaos and scattering off of other massive bodies in the outer Solar System.

This discovery implies that there must be a large population of TNOs in an 'extended scattered disk' with perihelia above the previously-suggested 38 AU boundary. The total population is difficult to estimate due to the ease with which such objects would have been lost. This illustrates the great value of frequent and well time-sampled recovery observations of trans-neptunian objects within their discovery opposition.

III References

Dones, L. 1997. In *From Stardust to Planetesimals*, ASP Conference Series V. 122, eds. Y. Pendelton and A. Tielens, 347.

Gladman, B. & Kavelaars J. (1997) Kuiper Belt searches from the Palomar 5-m telescope. *Astron. Astroph.* **317**, 35-38.

Gladman, B. Kavelaars J., Nicholson, P., Loredo, T., Burns J.A. (1998) Pencil-Beam surveys for faint trans-Neptunian comets. *Astron. J.* **116**, 2042-2054.

Gladman, B., P. Nicholson, J.A. Burns, JJ. Kavelaars, B. Marsden, G. Williams, and W. Offut. 1998. Discovery of two distant irregular moons of Uranus. *Nature* **392**, 897-899.

Goldreich, P., Murray, N., Longaretti, P., Banfield, D. 1989. Neptune's story *Science* **245**, 500-504.

Jewitt, D., Luu, J., & Trujillo, C. 1998. Large Kuiper Belt Objects: The Mauna Kea 8k CCD Survey. *Astron. J.* **115** 2125-2135.

Levison, H., Lissauer, J., Duncan, M. 1998. Modeling the diversity of outer planetary systems. *Astron. J.* **116**, 1998-2014.